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Potential impact of shifting coal to gas and electricity for building sectors in 28 major northern cities of China

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HIGHLIGHTS

- City-level building energy consumption were evaluated by spatial downscaling framework.
- Coal substitution policy would contribute 42% to future gas demand in northern China.
- Emission reductions were much more significant in 28 cities under stricter control.
- Electricity based clean heating might be more suitable than gas for rural households.
- Net social gains are expected when health and climate benefits were considered.

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ABSTRACT

Building sector accounts for about 30% of total primary energy consumption in Chinese cities, in which the untreated scattered coal is one of the most important sources for local air pollutants such as SO_2, NO_x, $PM_{2.5}$ and carbon emissions, posing serious threats on air quality, public health and climate change. This work aims to evaluate the impacts of the coal substitution policy ("coal-to-gas" and "coal-to-electricity") on building energy demand and emissions for Beijing, Tianjin, and other twenty-six cities along the "air pollution transmission channel", which has not been fully studied before and could assist city policy makers in coping with this drastic energy transformation by weighing potential social costs and benefits. To this end, a systematic method to downscale building energy consumption from provincial/regional level to grid level ($0.1^\circ \times 0.1^\circ$) is developed using openly available data and information to establish high resolution emission projections of CO_2 and major air pollutants (SO_2, NO_x and $PM_{2.5}$) for these cities. This framework provides a convenient way to simulate the spatiotemporal dynamics of future emissions by sector for multiple cities. Combined with three coal substitution scenarios designed in this study, some policy suggestions on alternative energy and social welfare improvement were made by investigating city scale effects on energy accessibility, affordability, as well as health and environmental benefits.

1. Introduction

The severe haze problem that has frequently plagued northern China in recent years, especially Beijing-Tianjin-Hebei (BTH) region and nearby cities during the heating season, has called tremendous attention to emission control for the improvements of air quality and public health [1]. Low-carbon development of this capital region is also leading national city-level climate actions. Besides various production and emission related restrictions imposed on heavy-polluting industries, power generation and vehicles [2,3], the requirement of clean energy transformation has also been raised for area emission sources represented by the building sector. One of the most important measures is stopping the use of scattered coal, which is widely adopted as major heating fuel by private and public buildings in rural/suburban areas. Researches show that although the unregulated scattered coal accounts for only 10% of the total coal consumption in BTH regions, it contributes more than half of the major air pollutants emissions due to its relatively poor fuel quality and low combustion efficiency [4].

In the "Air Pollution Prevention and Control Action Plan for Beijing, Tianjin, Hebei (BTH) and Surrounding Areas in 2017" proposed by Ministry of Ecology and Environment of China [5], Beijing, Tianjin and other twenty-six cities along the "air pollution transmission channel" ("2 + 26 cities" hereafter) in four neighboring northern provinces, have been required to cut down major air pollutant emissions more rapidly

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and thoroughly than other regions. Winter clean heating in the building sector is one of the central parts of the control strategy, aiming to strictly limit coal consumption and use clean energy represented by natural gas (NG) and electricity as substitutions. More specifically, small-scale coal stoves would be superseded and household coal-based heating system would be replaced by equipment fueled by NG and electricity, so that the coverage of coal-free zone would rapidly be expanded. In fact, during the combat against winter air pollution in 2017, scattered coal use has been reduced by 10 million tons due to coal-to-gas/electricity heating transformation in 4 million households, leading to 35% decline of ambient PM2.5 concentration for "2 + 26 cities" [6]. However, swift promotion of the coal substitution policy has also raised social contentions about the cost and reliability of clean energy retrofits, and was considered as an important cause for severe NG supply shortage in northern China. This implies that real world policy making is usually a compromise of various limiting factors rather than the result of energy system optimization. So how to make use of different information sources to quantify possible losses and gains for specific cities is of practical value, which is the main objective of this study.

Cities have drawn more and more attention on the way to sustainable development of China, from the perspectives of both public policy and academic research. This is not only because the fast expansion of urbanization has changed and highlighted the role played by cities in energy related emissions [7], but also because that city is often considered as the most appropriate scale at which to execute mitigation actions under China's administrative division [8,9]. However, most of relevant studies focusing on cities either covers only one or several large cities [10,11] due to the scarce of city-level data, or employed the input-output model [12] or carbon satellites data [13] that could not be widely applied to most Chinese cities. Although there are actually few researchers who have conducted multi-city studies by using unique dataset [14] or existing statistic yearbooks [8], their main objectives are methodology establishment or evaluations of historical emission patterns rather than future projection. Wu et al. [15] designed several production scenarios to examine CO_2 emission efficiency and productivity in 286 Chinese cities. However, sectoral information are lacking, making it difficult to account for pollutant emissions other than CO_2.

Despite the growing attention given to building energy savings, researches on pathways of pollutant emission reductions and carbon mitigation for China's building sector are still limited compared with other sectors. For example, as the most important CO_2 emission contributor to Chinese emissions, power sector has been extensively studied regarding its emission trajectory and mitigation pathway under different assumptions, with methods or models ranging from decomposition algorithms [16,17] to CGE [18,19] and technology based models [20]. Researches for major industries such as cement production [21], iron and steel [22] also abound for cities featuring different industry structures. And the relationship among different industries in terms of CO_2 emission caps has also been investigated [23]. As vehicle has become one of the most fast growing emission sources in Chinese cities, some policy scenario analyses were made to identify the cost-effective vehicle emission reduction policy tools [24,25]. Based on the establishment of a high resolution vehicle emission map for BTH region, Yang et al. [26] looked into the impacts of different control strategies on emission reductions and cost increase, suggesting that eliminating old vehicles and upgrading oil quality would be more efficient. Besides, there often exists large uncertainty among different studies due to the lack of reliable and accessible data, and it is well acknowledged that coal consumption by the residential & commercial sector is significantly underestimated by China Energy Statistic Yearbook [27]. Some researchers have tried to more accurately characterize energy consumption pattern of typical Chinese buildings by conducting national or city-level field surveys [28], ranging from rural households in northern China [29] to commercial and office buildings in southern cities [30]. In addition to the "bottom-up" framework adopted by most city-level energy and emission studies, Shan et al. [31] developed a systematic method for calculating CO_2 emissions for Chinese cities, using population as index to deduce emissions of cities from that of the corresponding province. With respect to future building energy demand and emissions predictions for Chinese cities, simulations tools and statistical models have been applied based on various control scenario [32–34], including the recent coal-forbidden policy in BTH region and the energy efficiency improvement technologies in China's hot summer and cold winter zone [35,36]. Several studies have looked into the spatial heterogeneity in building energy consumption/emission by establishing high resolution energy use map. For instance, Winijkul et al. attributed global residential emissions to geographic units from national statistics by end-use and land types [37], and extended the scheme, which accounts for spatial constraints on residential fuel use, to reduction scenarios. Pereira et al. [38] and Lin et al. [39] combined energy demand model rich in technological details for individual buildings with socio-economic parameters, so that building energy use in Belo Horizonte, Brazil (by census block) and in two urban areas, Taiwan (by grid) were respectively presented. Similar studies differing in area of interest are commonly conducted to facilitate local energy policy making [40–43]. However, most of the researches rely on detailed data-driven models to study spatial and temporal patterns of building energy use, which is not suitable for multiple-city simulations for most Chinese regions with limited data accessibility. Moreover, among scenario-based building energy consumption predictions for cities, few has incorporated national/provincial planning targets, or considered potential impacts of geographic distribution changes of socioeconomic variables (e.g. population, urbanization rate) inside cities.

Compared with existing knowledge on city-level energy management, the originality of this study might be manifested as follows. From the aspect of research topic, this is the first time that "2 + 26 cities" is studied, on which the impacts of the recent scattered coal substitution policy are quantitatively evaluated from the perspectives of energy sustainability and emission reductions. From the aspect of research methodology, this study developed a systematic downscaling method to allocate provincial building energy consumption to city and grid level by accounting for the spatiotemporal changes of socioeconomic drivers. This would help lower the uncertainty of constructing city-scale emission pathways compared to the relatively simple allocation framework based on historical emissions, and could also combine the advantages of both bottom-up and top-down models by simultaneously considering provincial energy/emission control targets and city level low-carbon development strategies. From the aspect of policy relevance, scenario comparisons and social cost and benefit analysis conducted in this study might lend quantitative support to the choice of alternative energy and the adjustment of policy according to the development status of different cities. It is expected that the results of this work might be applied to other Chinese cities and other sectors in the future.

2. Methodology

2.1. Overview of the research framework

The study area in this work covers Beijing, Tianjin and other twenty-six cities located in four provinces around (Hebei, Shanxi, Shandong and Henan), such as Baoding, Langfang and Taiyuan. And the complete city list can be found in Supplementary Material (SM) Table 4.

Provincial energy consumption is the basic information required for city and grid-scale inventory construction, which includes both historical trend and future predictions. Then downscaling was performed to allocate fuel consumption data from relatively coarse spatial resolution (region/province) to finer ones (city/county/grid). The research framework, including the possible applications to city-level energy and environmental policy making with the combination of GIS platform, is shown in Fig. 1. Various types of statistics and information involved are summarized in Table 1.

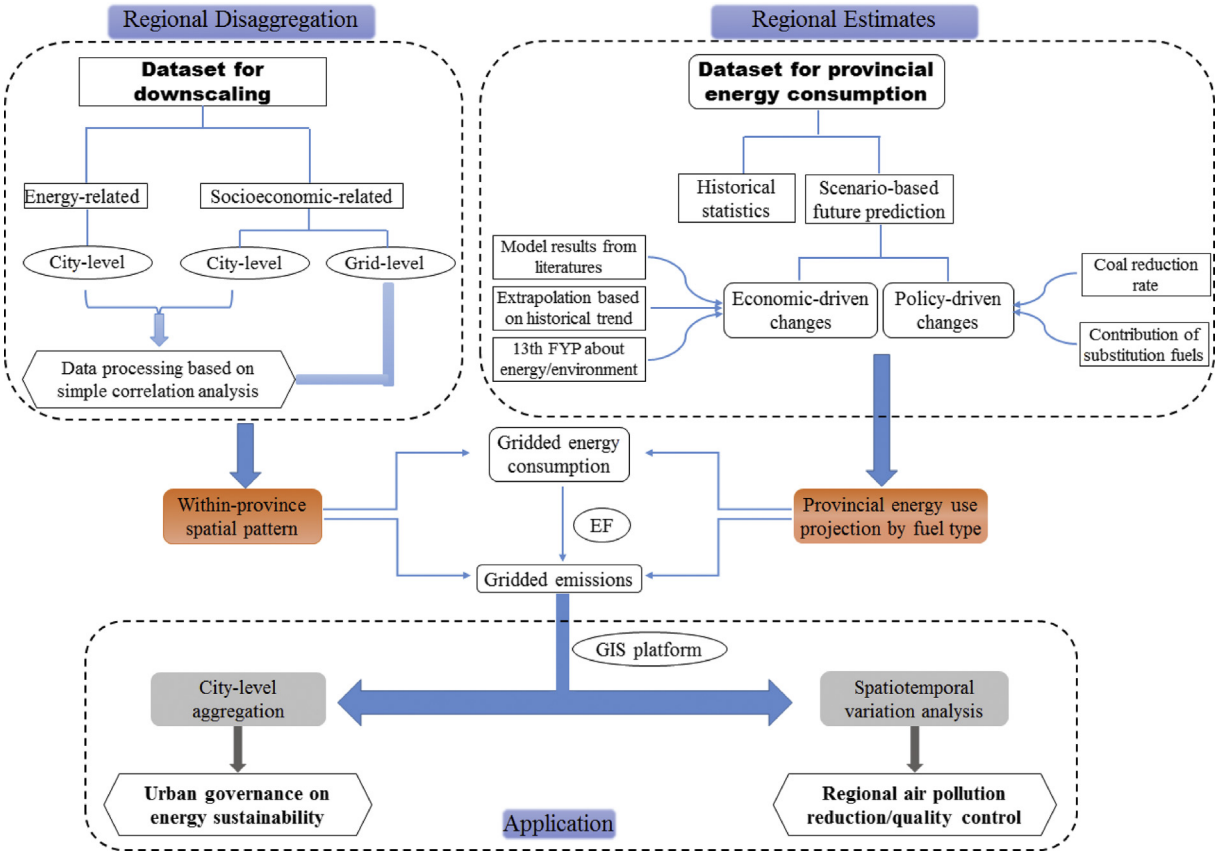

Fig. 1. Flow chart of the research framework.

Both emissions of CO_2 and major air pollutants are calculated by multiplying activity data (building energy consumption) with emission factors (SM Table 2). As the common practice of most studies concerning energy and emission performance of buildings [44], the building sector includes the residential sector (urban and rural buildings) and the wholesale services proposed by IPCC sectoral approach [45], which is different from the consumption-based accounting approach [46,47]. When calculating indirect emissions from electricity and heating consumption, it is assumed that their demand by the buildings within the administrative boundary of a city were supplied entirely by the province it belongs to. So without considering inter-province electricity transmission, the indirect emission factors of power and heating use for a city remains the same as the provincial average, which were calculated based on electricity/heat production and fossil

Table 1
Major sources of data and information used in this study.

	Data source	Spatial resolution (Year)
Energy-related data	China Energy statistics	By province (1996–2016)
	Scattered coal consumption [48] (Huo et al., 2017 (in Chinese))	By province (2014)
	Liao et al., 2017 [49]	By province (2020)
	Statistical Yearbooks	One single province/municipality (2015)
	Economic Yearbooks	
	13th Five-Year-Plan for Energy Development	One single province/municipality (2015–2020)
	13th Five-Year-Plan for Natural Gas Development	
	13th Five-Year-Plan for Urban Heating Development	
	13th Five-Year-Plan for Energy Conservation and Emission Reduction	
Downscaling-related data	China Urban Construction Statistical Yearbook	City (2015)
	China City Statistical Yearbook	
	Gridded urban/rural population and distributions of urban areas in China [29] (Shen et al., 2017)	30 arc second (2010, 2030)
	Gridded GDP of China [30] (Huang et al., 2014 http://www.resdc.cn/data.aspx?DATAID=121)	1 km (2010)
	Gridded population of the world	0.5° × 0.5° (2010, 2020)
	SSP public dataset (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=series)	
	Gridded GDP of the world	0.5° × 0.5° (2010, 2020)
	SSP public dataset (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=series)	

Note: Since 0.5° × 0.5° population and GDP are provided every ten years since 1980 in SSP2 dataset, to obtain the 0.5° × 0.5° gridded data for 2015, we take the average value of 2010 and 2020 as an approximate. After that, we use the spatial patterns of urban/rural population in 2010 from Shen et al. [50], which is presented with higher resolution, to further downscaling them to the 0.1° × 0.1° grid. The same method is applied for GDP, which is provided by Huang et al. [51].

fuels consumed by thermal power plants.

2.2. Provincial energy consumption projection by fuel type

Considering that the main purpose of the "2 + 26 cities" policy for the building sector lies in promoting energy structure shift from scattered coal to clean fuels exemplified by NG, electricity and central heating, this study focuses on the consumptions of these four types of energy widely used in China's building sector (urban, rural residential buildings and commercial buildings). Coal reduction rate for the four provinces and two municipalities were determined based on multiple information sources listed in SM (Table 1). For NG and electricity consumption, the expected increases in 2015–2020 are generally assumed to be driven by both economic development and the coal substitution policy. For the economic-driven "voluntary increase" of clean energy use in residential buildings, provincial NG consumption growth is estimated based on the planned increase of the population accessible to pipeline infrastructure in the area of interest, while the projection of electricity consumption comes mainly from the research work of Liao et al. [49] conducted by piecewise linear model. Note that due to the lack of quantified information about the transformation from coal to central heating, it is difficult to estimate its newly increased consumption caused by the coal substitution policy. Therefore central heating use in 2020 was predicted according to the target of urban heating coverage expansion prescribed in regional 13th Five-Year-Plan (FYP). Generally this assumption would not make notable difference since central heating substitution accounts for a much smaller share compared with NG and electricity because of the difficulty in its application to rural areas. For the policy-driven increase of NG and electricity demand, the substitution contribution from NG and electricity should be determined at first, and the overall approach can be described as follows: for regions (e.g. Tianjin) which set specific objectives concerning the number of households ready for NG/electricity retrofits by 2020 [52], these planned values were used for estimation; while when little or no future information is available, some simple but reasonable extrapolations were made based on current situations. For instance, the drastic coal-to-gas movement has led to the over fulfilment of the expected transformation task in Hebei province in 2017, which was considered as part of the causes of gas supply shortage. Hence it is assumed that NG substitution in Hebei would slow down and temporarily stop in 2018 until there is new source of supply, and the magnitude of the transformation in 2019 and 2020 would be smaller [53]. It is predicted that the number of households that switch to NG-based heating system would reach 4.5 million by the end of 2020. In this way, the relative contributions of NG and electricity to scattered coal substitution can be derived when combined with the conversion parameters provided in SM (Table 2).

2.3. Downscaling from province to grid and city level

To derive city-level energy consumption and emissions from available information, the process of spatial downscaling is necessary and effective, which means that energy consumption data provided by province needs to be further disaggregated into finer scale (grid-level in this study) based on a series of rules and reasonable assumptions. For example, for Hebei province, historical NG and electricity consumption statistics of its major cities in 2015 was used to explore the possible correlations between per capita household energy use and socioeconomic parameters (e.g. population, GDP per capita and urbanization rate). Then these quantified relationships were applied to grid-level socioeconomic factors (Table 1) to generate spatial proxies required by downscaling. In this way, gridded energy consumption map ($0.1^\circ \times 0.1^\circ$) can be produced from provincial projections. Note that for grids within the boundaries of "2 + 26 cities", coal reduction rate was set to be higher than other grids in response to stricter policy enforcement within these areas, reflecting the fact that more prominent energy transformation would occur in these targeted cities. Under these assumptions, newly increased NG consumption owing to the coal substitution policy for "2 + 26 cities" was estimated to be 9.0 billion cubic meters, comparing well with the objective proposed in "Clean winter heating plan for Northern China (2017–2021)" [54], which states that NG consumption increase contributed by gas wall heaters would reach 9.1 billion cubic meters by 2020. While for the disaggregation of commercial energy use, grid-level GDP was employed as simple but effective spatial proxy.

2.4. Scenario design

Although the estimations on building energy consumption and related emissions for "2 + 26 cities" in 2020 were carried out according to regional 13th FYP and other officially released documents, there still exists large uncertainty concerning energy policy and market in the next few years. This study focuses on two important variables associated with policy impact—the reduction rate of scattered coal and the relative contributions of the newly increased NG/electricity to total coal substitution. The former is related to the stringency of policy implementation, and the latter is related to the uncertainty in city-level strategy. Therefore for building energy consumption in 2020, there are four scenarios (Table 2) investigated in this study to explore possible ranges of energy savings and emission reductions achieved by coal-to-gas/electricity strategy. S0 represents scenario in which the goals of scattered coal control and fuel substitutions would be reached by following existing substitution plans, and S1-S3 represent scenarios in which the scattered coal in the building sector of the six provinces/municipalities would be entirely eliminated. The three strict coal-forbidden scenarios differ in the relative contribution of NG and electricity as substitution fuels.

2.5. Estimation of social costs and benefits

Social costs and benefits were estimated for "2 + 26 cities" under S1, in which the building sector would stop using scattered coal by 2020. In this study, social benefits include both health benefits and climate benefits. The former comes mainly from disease-induced labor productivity loss that could be avoided due to reduced indoor air pollutants emissions, and the latter refers to the value of damages avoided due to reduced CO_2 emissions, which are both made possible by freeing from scattered coal related pollutions. The general approach follows Jin et al [55], and the benefits and costs covered are listed in Fig. 2. Parameters required by cost and benefit calculations are provided in SM

Table 2
Description of scenarios designed in this study.

Scenario Acronym	Coal reduction rate		Relative contributions of NG and electricity to coal substitution	
S0	Beijing: 90%	Tianjin: 85%	Beijing: 1:3	Tianjin: 1:1
	Hebei: 60%	Shanxi: 55%	Hebei: 3.25:1	Shanxi: 6:1
	Shandong: 60%	Henan: 50%	Shandong: 1:1.35	Henan: 1:1.8
S1	100% for all provinces/municipalities		The same as values under S0	
S2	100% for all provinces/municipalities		The contribution of NG is set to increase by 20 percentage points compared with values under S0	
S3	100% for all provinces/municipalities		The contribution of electricity is set to increase by 20 percentage points compared with values under S0	

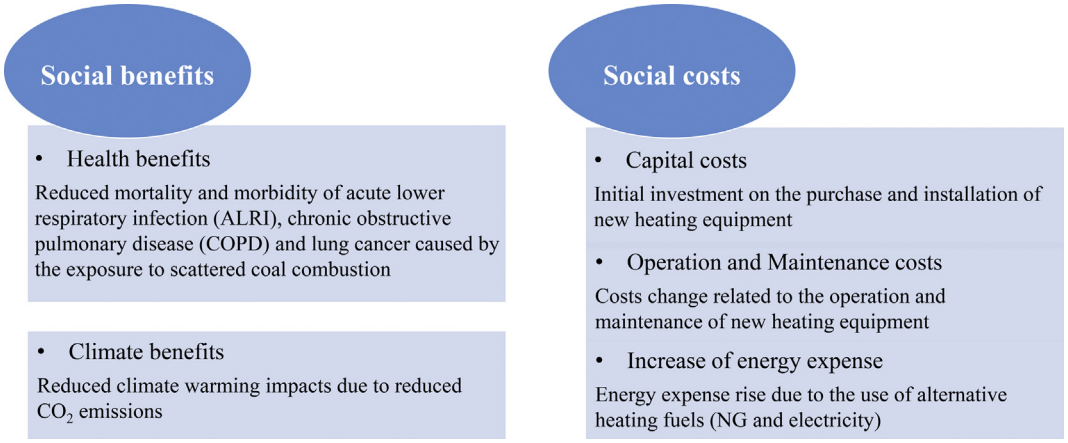
Social benefits
• Health benefits
Reduced mortality and morbidity of acute lower respiratory infection (ALRI), chronic obstructive pulmonary disease (COPD) and lung cancer caused by the exposure to scattered coal combustion
• Climate benefits
Reduced climate warming impacts due to reduced CO_2 emissions
Social costs
• Capital costs
Initial investment on the purchase and installation of new heating equipment
• Operation and Maintenance costs
Costs change related to the operation and maintenance of new heating equipment
• Increase of energy expense
Energy expense rise due to the use of alternative heating fuels (NG and electricity)

Fig. 2. Social benefits and costs brought by scattered coal substitution policy for the building sector discussed in this study.

Tables 5 and 4 for the fuel price. It should be noted that to simplify the estimation process, this study does not account for the engineering costs of NG pipeline construction, which might vary significantly with local conditions and might be an important part of national/provincial infrastructure investment not exclusively built for "coal-to-gas" policy intervention. Also, there are some benefits that are not included, such as the hedonic/aesthetic value of better living environment.

2.5.1. Health benefits resulting from scattered coal clean up

In this study, the subject of health effects is the population exposed to indoor pollution caused by coal combustion, which could be represented by the share of households using scattered coal as major heating fuel. The end point of health effects includes three kinds of diseases considered by WHO [56], namely acute lower respiratory infection (ALRI) for children under 5 years old, chronic obstructive pulmonary disease (COPD) and lung cancer for adults over 30 years old. The decrease in mortality and morbidity attributed to these diseases were chosen as quantitative indicators. The health effects were estimated as follows,

$$HE_{ipq} = AP_{ipq} \cdot I_{ipq} \cdot POP_{pq} \quad (1)$$

where HE_{ipq} is the health effects of disease i for population by age (p) and gender (q). AP_{ipq} is the proportion of people with disease i which could be attributed to exposure in population by age p and gender q. I_{ipq} is the incidence of disease i, which reflects the number of new cases in a given period of time among the population at risk. And POP_{pq} is the population size by age p and gender q.

$$AP_{ipq} = \frac{1}{1 + [PE_{pq}(RR_{ipq} - 1)]^{-1}} \quad (2)$$

where PE_{pq} is the percentage of people exposed among the population by age (p) and gender (q). RR is the relative risk of indoor coal usage suggested by WHO [56]. Note that improved coal, stoves and ventilation are all helpful in reducing exposure, so ventilation coefficient is applied to adjust PE_{pq} so that the health effects would not be overestimated [57].

2.5.2. Monetize health benefits

Value of a statistical life (VSL) is widely applied in monetizing health impacts induced by environmental pollution or emission reductions [58], and is defined as the marginal substitution rate between mortality risk and economic welfare. Note that the benefits from reduced mortality caused by chronic diseases, discount should be made to account for the delay before illness onset. Here we combine the social discount rate (r, 3%) and years of delay (t, 20 years) to construct discount factor $e^{-r \cdot t}$. Besides, this delay would also require necessary VSL adjustment by average annual income growth rate and income elasticity of VSL [59]. The detailed setting of the involved parameters are provided in SM Table 5.

2.5.3. Climate benefits from CO_2 reductions

Social carbon cost (SCC) is the marginal economic damage linked with per unit CO_2 emissions increase. Following US EPA [60], mean global SCC is set to be 40 US$/ton CO_2, with 12 and 200 as the lower and upper bond, respectively. Here we use China national value of SCC and assume it to be one quarter of the global value as suggested by Gayer and Viscusi [61]. Climate benefits were quantified by multiplying SCC with CO_2 emission reductions achieved through using lower emission energy instead of scattered coal. Note that we did not further account for the contributions from emission reductions of other greenhouse gases (except for CO_2) since the magnitude of climate benefits is much smaller compared with health benefits.

3. Results and discussion

3.1. Building energy consumption changes under scattered coal substitution policy

3.1.1. Changes of spatial distributions

For four building energy sources studied in this work, Fig. 3 illustrates the spatial distributions of their consumptions in 2015 and 2020, respectively. Nearly 100 million tons of scattered coal was consumed by building sector in this region in 2015, of which 78% was burned by rural residents. Following current reduction pathway, it is estimated that the amount of consumption would significantly drop to only 40 million tons by 2020. Generally urban areas are expected to experience more radical coal removal campaign (74%), reflecting the stricter coal-free requirement in more populated areas [62]. As a result, scattered coal that used to prevail in the "urban villages" and suburban areas would be rapidly replaced, leaving the remaining coal in 2020 exist only in remote rural regions.

It is found that the locations with most significant NG increase match well with those subjected to more significant coal reduction, indicating that the coal-to-gas project would act as an important impetus for NG demand increase. Per capita NG consumption of the building sector is expected to rise by about one fold compared with that in 2015, which would ask for rapid growth of pipeline system. Therefore NG consumption tends to be more evenly distributed across this region in 2020 due to the increased fuel accessibility. Meanwhile, it is estimated that electricity consumption in the building sector of the six provinces/municipalities would increase by 202TWh, of which about 17% would be contributed by the promotion of coal-to-electricity. In addition, larger growth potential of electrification rate in rural areas would also help narrow the gap of electricity consumption

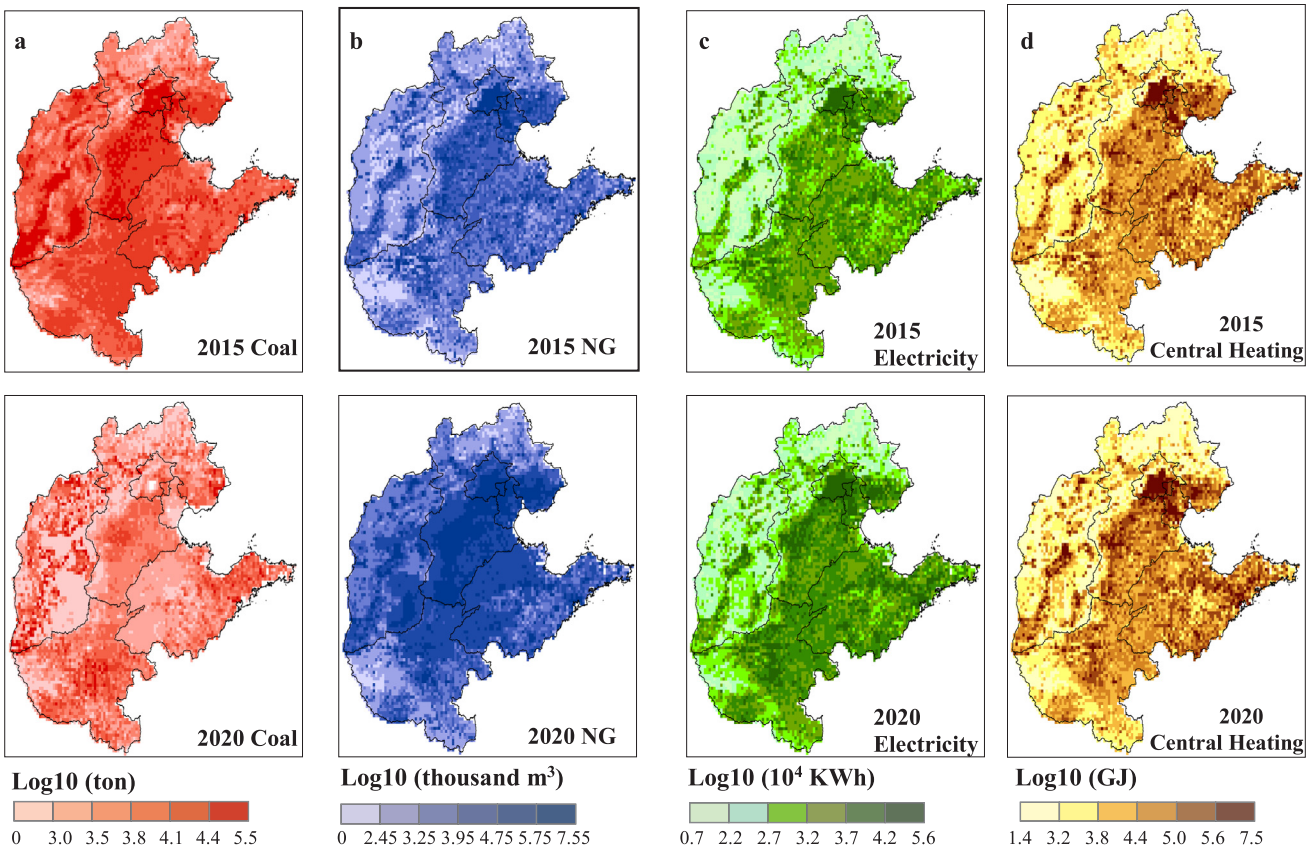

Fig. 3. Spatial distributions of building energy consumption by fuel type in 2015 and 2020 for the six provinces/municipalities.

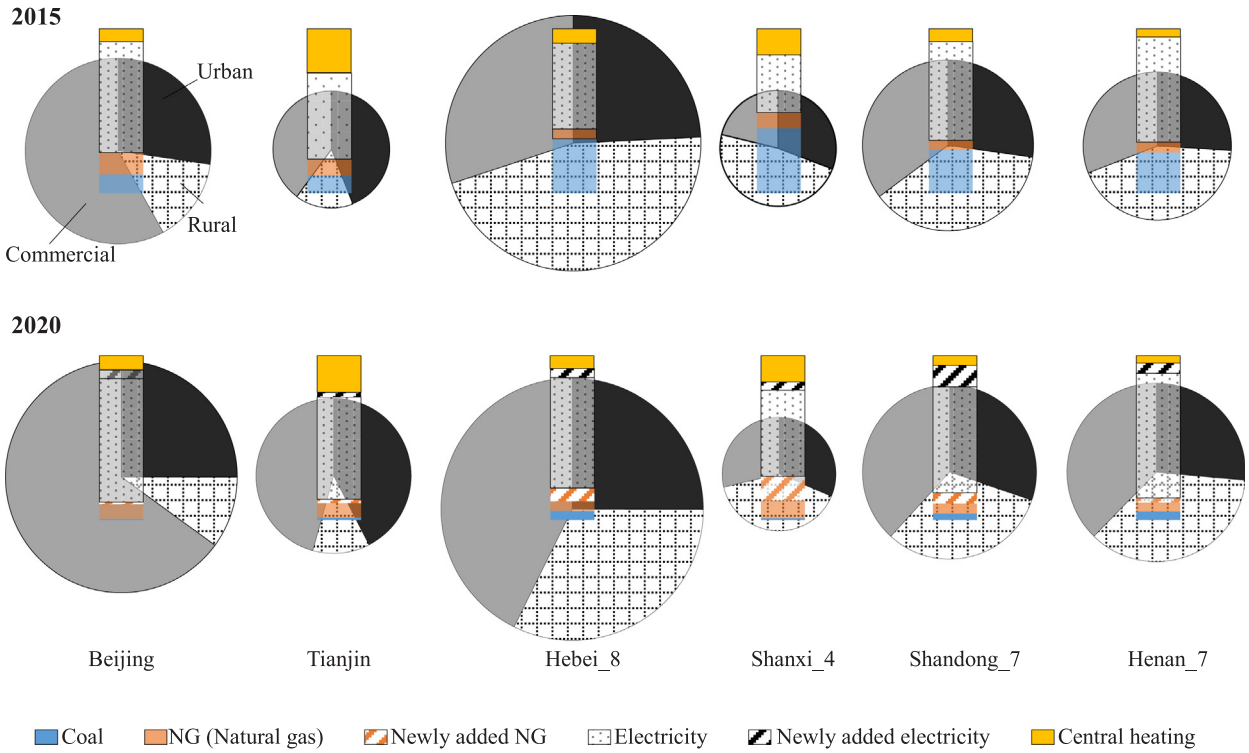

Fig. 4. Compositions of building energy consumption in "2 + 26 cities" in 2015 and 2020.

level between urban and rural residents. Central heating coverage would also get enlarged with the expansion of urban built area and the migration of population. Taking Shandong province as an example (Fig. 3(d)), one of the hotspot regions located in Jinan and Zibo, two large cities with relatively higher urbanization rate, would be gradually trending eastward to the counties/towns belonging to the city of

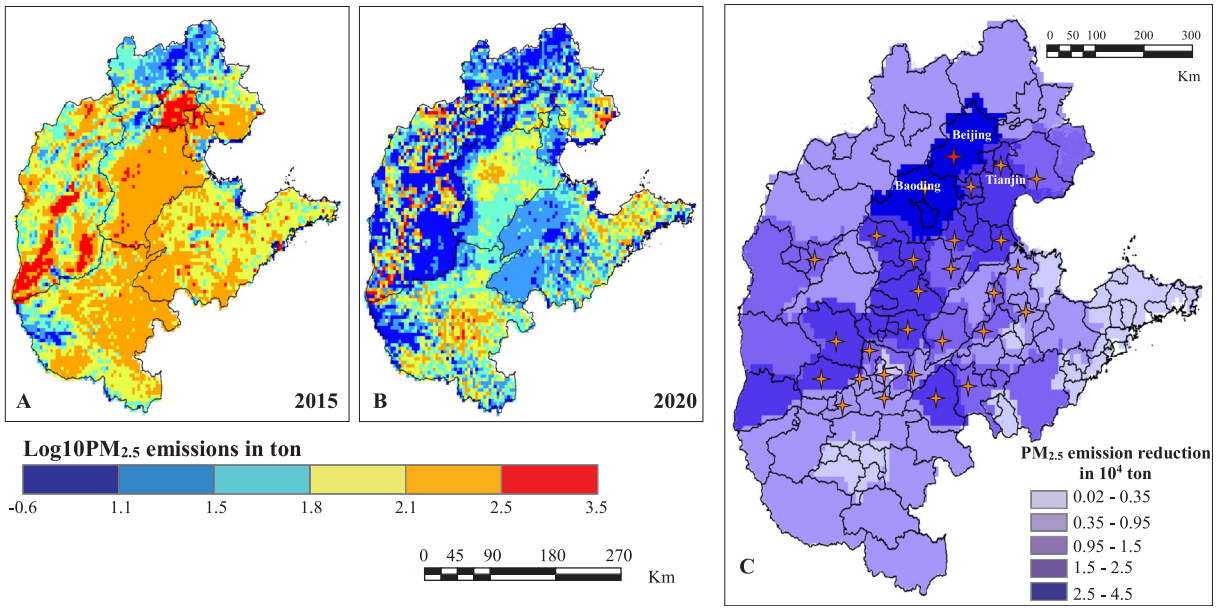

Fig. 5. Spatial distributions of log-transformed $PM_{2.5}$ emissions in 2015 (A) and 2020 (B). And $PM_{2.5}$ emission reductions by city (C).

Weifang by 2020. It is projected that central heating demand of the non-urban areas within "2 + 26 cities", where heating supply network was seldom covered in 2015, would increase by 17.2% in 2020.

To validate our modelling results on cities' building energy consumption, comparisons with estimations from other studies are needed as suggested by Li et al. [63], given that scientific experiment regarding energy consumption of the whole city could hardly be conducted. However, to the best of our knowledge, there are very few studies which have investigated city-level energy use by fuel type and by sector, especially from future perspective. And this is one of the reasons why this study is done to better guide policy making. To verify the reliability of the downscaling method developed in this study, some local surveys from reports on several cities' household scattered coal consumption in 2015 were adopted [64–66], which show that annual scattered coal consumptions in outskirts and rural areas of the city Shijiazhuang, Baoding and Taiyuan are about 4, 5 and 1.1 million tons, respectively. And our corresponding estimations are 3, 4.34 and 1.21 million tons, showing good match with acceptable deviations around 10–24%. To testify the assumptions used by this study in predicting the policy-driven clean energy increase, we used newly increased electricity demand in Beijing and Tianjin as examples, which are the only city-level predictions that could be found. According to their proposed scale of transformation and average consumption level [67–69], the involved households are expected to consume 4110 GWh and 1920 GWh more by 2020, which compare well with our modeled results (5810 GWh and 1440 GWh).

3.1.2. Changes of building energy consumption structure

After adding up grid-level fuel consumption by city, building energy consumption structures of Beijing, Tianjin and other twenty-six cities in the four northern provinces could be figured out and shown in Fig. 4. More stringent enforcement of the coal substitution policy in these cities would help cut down scattered coal use by 41 million tons, equivalent to 20% of the national control target set for 2020 (200 million tons). The coal reduction rate of "2 + 26 cities" would reach as high as 80%, a lot higher than other cities of these provinces, and this is especially true for the four cities in Shanxi province, where the share of coal in total building energy use would drop significantly by 35%.

Predictions based on planned reduction efforts suggest that another 9 billion cubic meters of NG demand would be induced by the "coal-to-gas" policy in the twenty-eight cities, among which 82% would come from Hebei, Shandong and Shanxi. It is estimated that the policy-driven NG consumption increase would account for more than half of the total consumption in the building sector of these three provinces in 2020. However, this increase would make less difference for Beijing, Tianjin and Henan since electricity-based heating equipment would also play an important role in coal substitution. It was reported that among all villages that have completed clean energy retrofits in Beijing, 87.2% and 71.4% of them were required to install electricity heating in 2016 and 2017, respectively. On the other hand, the share of electricity would increase by 18.6% on average for "2 + 26 cities", making it the leading energy source even for rural households in 2020. This is also the reason why the magnitude of the policy-driven increase would be relatively smaller (equivalent to 9.2% of the total consumption in 2020) compared with that of NG. In this sense, substitution by electricity might not introduce potential threats for reliable energy supply in the building sector, but instead a promising way to solve the problem of electricity oversupply. Although the accessibility of central heating is gradually increasing in towns or even large villages with relatively higher population density, it is not expected to rapidly scale up before 2020 considering the relatively long construction period. Hence the share of central heating would generally remain stable.

Energy consumption contributions from the three subsectors (urban, rural and commercial) would also differ from those in 2015. The proportion increase of commercial buildings and the decrease of rural residential buildings are the common features of all regions. Besides, most of the scattered coal reductions would occur in rural households with faster income growth, leading to a boost of electricity demand in 2020 for rural areas, in which NG consumption would even be doubled compared to that in 2015. Meanwhile, the transformation towards cleaner energy would also be conducive for the overall efficiency enhancement. Therefore, along with rural residents' continuous migration to urban area, the share of rural residential building energy consumption is estimated to decline from 35% to 25% during the studied period.

3.2. Direct emission reductions under scattered coal substitution policy

Replacing coal with NG and electricity could cut carbon emissions down by 106.7 Mt CO_2 for the involved six provinces/municipalities. More importantly, it would also be an effective way to address haze pollution. As in the case of Hebei, to ensure the $PM_{2.5}$ concentration limit set for 2020 (57/m^3), emissions of SO_2 and NO_x, two important

precursor of secondary $PM_{2.5}$, need to be respectively reduced by 387 and 311 thousand tons [70]. Hence the estimations from this study implies that phasing out scattered coal from the building sector alone would help achieve 60% and 8% of the overall targets, respectively. Taking $PM_{2.5}$ as an example, Fig. 5 illustrates the spatial distributions of emissions from building energy use in 2015 and 2020. According to the calculations, direct $PM_{2.5}$ emissions (indirect emissions from electricity and central heating were not included) from the building sector was 971 thousand tons in 2015, and is expected to decline to 400 thousand tons by 2020. Generally, emission reductions would be stronger for Beijing, Tianjin, Hebei and Shanxi (Fig. 5(A and B)), and the emission density in grids within the urban areas would be much lower.

Moreover, "2 + 26 cities" would experience more notable emission reductions compared to other cities (Fig. 5(C)), and are expected to contribute 70% to the total reductions achieved by the building sector within the entire region. Among the twenty-eight key cities, Beijing, Baoding and Langfang would be the leading ones in terms of absolute reductions, while the four cities in Shanxi Province would perform better in terms of relative emission reductions of $PM_{2.5}$ and SO_2 (about 90%). According to the statistics, during 2016 and 2017, 3 million and 5.78 million households have respectively shifted from the traditional coal-based heating system to that fueled by clean energy, leading to evident air quality improvement within the BTH region. Monitoring data has indicated that the ambient concentration of $PM_{2.5}$ of the "2 + 26 cities" during the heating season in 2017 have dropped by 35% compared to the same period in the previous year. However, for CO_2 and NO_x emissions from the building sector, the reduction rates would be relatively lower than that of $PM_{2.5}$ and SO_2, which might be explained by the fact that their emissions from the direct combustion of NG could not be neglected. For example, when compared with Jincheng, Changzhi, and Yangquan, in which CO_2 and NO_x emissions would be reduced by 65%, the reduction rate of Taiyuan, the capital city of Shanxi province with higher economic development level, would be even lower due the relatively greater popularity of NG substitution.

3.3. Scenario comparisons and policy impacts analysis

Besides previous discussions under planned scenario S0, in this section, three coal-forbidden scenarios (S1, S2 and S3) with different assumptions on fuel substitutions are investigated, aiming to explore different policy impacts by scenario comparisons from the perspectives of emission reductions, energy accessibility and affordability.

3.3.1. Impacts on emission reductions

For "2 + 26 cities", building energy savings and emission reductions resulted from the coal substitution policy during 2015–2020 under different scenarios in 2020 is shown in Table 3. Note that energy savings discussed here is defined as the energy consumption difference between that in 2015 and 2020, the same definition goes for emission reductions. On one hand, a complete ban on coal use in the future means larger amount of energy savings from the building sector because of the elimination of low-efficient and emission-intensive coal stoves. However, the greater penetration of gas-based heaters under S2 does not bring so much energy savings and carbon emissions as that under S3, in which electric heating, especially the more efficient air source heat pump, is more preferred. On the other hand, compared with SO_2 and $PM_{2.5}$ emissions (indirect emissions from electricity and central heating use included) in 2015, their total reductions induced by the coal substitution policy would be 24% and 39% higher under coal-forbidden scenarios (S1, S2 and S3) than that under planned scenario (S0). However, clean energy substitution in buildings does not necessarily help reduce total NO_x emissions given current pollution control technologies adopted by individual gas heaters and fossil-fuel power plants.

Table 3
Energy savings and emission reductions caused by the coal substitution policy for the building sector of "2 + 26 cities" (under different scenarios).

		S0	S1	S2	S3
Energy savings (PJ)		825	910	838	985
Emission reductions (indirect emissions from electricity supply is included) (10^4 ton)	CO_2	6365	7122	7036	7203
	NO_x	3.88	3.64	3.67	3.59
	SO_2	19.9	24.7	24.8	24.7
	$PM_{2.5}$	35.6	49.5	49.6	49.5
Emission reductions (indirect emissions from electricity supply is not included) (10^4 ton)	CO_2	7533	8835	7945	9759
	NO_x	5.76	6.40	5.14	7.71
	SO_2	20.3	25.2	25.0	25.4
	$PM_{2.5}$	40.1	49.9	49.7	50.0

If indirect emissions from electricity supply is not included in the building sector, reductions achieved by the coal substitution strategy would be more impressive, especially under S3 in which electricity is used as the major substitution fuel. For example, carbon mitigation under S3 is 10.5% and 22.8% greater than the levels under S1 and S2, respectively, and the advantage of S3 in terms of NO_x emission reductions would be even more remarkable. Comparisons between the two kinds of emission reduction estimations in Table 3 suggest that curbing emissions from building electricity consumption would be important for enhancing emission reduction potential of the building sector. Generally coal-to-electricity would hold more promise for overall emission reductions than coal-to-gas, which is made possible by the compulsory adoption of "ultra-low emission" technologies and decarbonization in the power industry. As a matter of fact, ultra-low NO_x emission standards is being rapidly popularized, with cumulative unit capacity reaching 570 billion KWh by the end of 2017, sharing 60% of the installed capacity of coal-fired power plants.

3.3.2. Impacts on NG supply and accessibility

As displayed in Fig. 6, per capita NG consumption in the building sector of "2 + 26 cities" in 2015 (62 m^3/cap) is about one seventh that in OECD countries (411.8 m^3/cap). However, with the deepening of energy consumption transformation until coal is entirely removed from the building sector as described in S1, the gap of the consumption level between "2 + 26 cities" and OECD countries would be soon narrowed. The growth potential of NG demand is especially high for the twelve cities in Hebei and Shanxi considering their large coal consumption bases and the preference for NG substitution.

On the other hand, the construction of natural gas supply/transport network in "2 + 26 cities" also lag far behind the average level of OECD countries. This is manifested by the comparison of pipeline density inside the city (Fig. 6), which is defined as the length of the gas distribution pipelines within unit living area. For instance, while per capita NG consumption in the building sector of OECD countries is 50% higher than that of Beijing in 2015, its pipeline network density (32.3 km/m^2) is about 2.1 times that of the latter (15.5 km/m^2). Actually among the twenty-eight cities, Beijing and Tianjin are the only two cities whose inner-city pipeline are relatively longer (21818 km and 19356 km, respectively) and gas transport capacity are comparable to that of developed countries. Therefore, if coal-to-gas is to be further insisted, it might be an urgent need and a challenging task to enhance NG accessibility as soon as possible in order to keep up with the annual growth rate of NG demand (15.6% and 21.8% under S0 and S1, respectively).

Besides the upstream gas source and inner-city pipeline network, strategic storage of natural gas on city level is also an important prerequisite for NG substitution. According to the overall target set for the six provinces/municipalities, in order to ensure reliable NG supply, the necessary emergency stock required for Beijing, Tianjin, Hebei, Shanxi, Shandong and Henan by 2021 is 170, 120, 210, 140, 230 and 160 million cubic meter, respectively. Even if these provincial storage targets could be attained as planned, the emergency coping capacity would still be quite limited, which could only sustain 4–10 days given

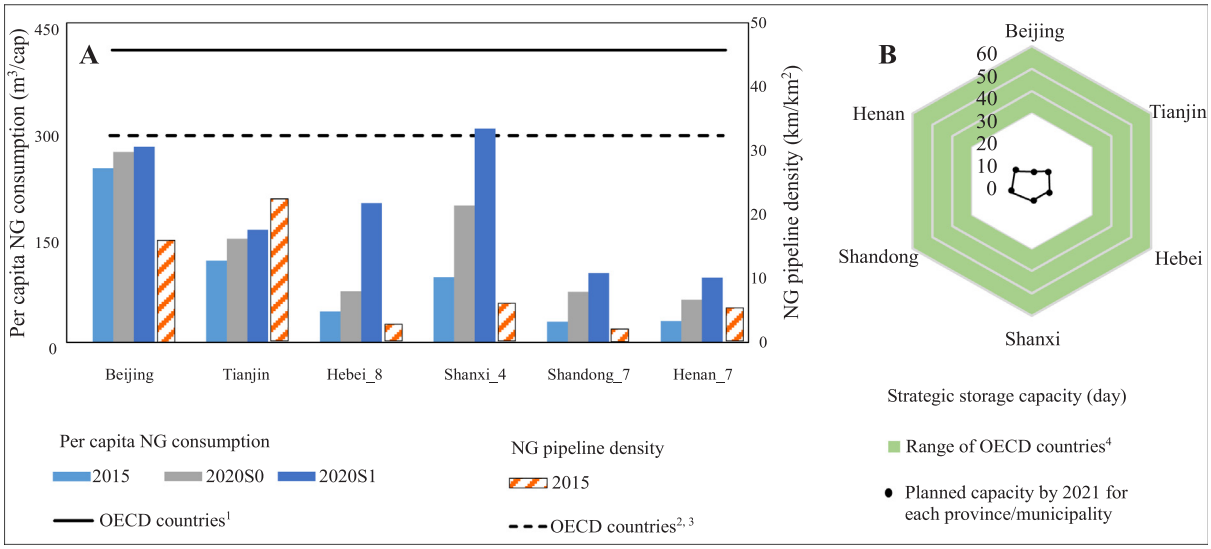

Fig. 6. Natural gas consumption per capita in 2015 and 2020 for "2 + 26 cities" under S0 and S1 (A), and planned storage capacity by 2021 for each of the six province/municipality (B). [1]International Energy Agency (IEA). http://www.iea.org/statistics/statisticssearch/. [2]Council of European Energy Regulator. 6th CEER Benchmarking report on the quality of electricity and gas supply. [3]Statistics and information from national energy regulators/associations/department by country. For example, for Canada, the data concerning the length of the distribution pipeline is from The Canadian Energy Pipeline Association (https://www.cepa.com/wp-content/uploads/2013/10/CEPA_Our-Energy-ConnectionsE_Oct04.pdf); for Austria, similar data is provided by E-Control (https://www.e-control.at/en/industrie/gars/gasnetz#). [4]International Energy Agency (IEA). Global gas security review 2017.

current daily consumption level. In contrast, the average strategic NG storage in OECD countries could meet the demand for 30–60 days (Fig. 6(B)). As a matter of fact, Chinese cities, except for megacities like Beijing, are seldom equipped with specialized gas storage infrastructure. Hence if NG is going to play a leading role in replacing scattered coal, then for the sake of energy supply security, substantial technical and financial supports have to be provided for the development of robust NG storage systems for each city.

3.3.3. Impacts on household energy affordability

Another obstacle facing clean heating transformation in the building sector is the relatively higher cost compared to the traditional stoves fueled by coal, especially for the rural households that are the main subject of the heating system retrofit. This section focuses on household energy expense increase to explore the policy impacts on energy affordability, especially for rural residents. Note that initial investment on engineering is not included in the discussion. The results displayed in Fig. 7 looks into the magnitude of energy expense increase and compare it with annual income of rural households in "2 + 26 cities".

It is found that a complete removal of scattered coal from the building sector would give rise to a significant energy cost increase compared to that under S0. And to evaluate the impacts of different substitution plans, energy expense rise under the three coal-forbidden scenarios (S1, S2 and S3) are further compared. On one hand, expense increase under S1, in which the relative contributions from NG and electricity remain the same as that under S0, tends to lie between the case of S2 and S3. On the other hand, the cost advantage of the substitution strategies adopted in S2 and S3 would be largely determined by local residential price of NG and electricity. Using lower-priced off-peak electricity makes electric heating more appealing for both cost reduction and power grid peak shaving, and most "2 + 26 cities" have released preferential policies to extend the valley price period. Therefore the energy expense increase under S3 would be smaller than that under S2 for most of the cities, except for those in Henan where the peak-valley electricity price difference is less impressive and residential NG price is relatively lower. Besides, for more developed cities like Beijing where rural families are relatively wealthier, the city government is usually more financially capable of implementing energy subsidy. It was reported that during the valley period, the actual electricity cost paid by rural households switching from coal to electricity heating would be only one quarter of the normal level in Beijing [71]. Even without these favorable economic incentives, it is still reasonable to expect that the overall cost of electricity substitution for the society would keep going down owing to technology and trading market development of the power sector.

When economic burden increase induced by clean fuel substitution is compared among rural areas of different cities, it is found that the energy bill of rural households in Jincheng, Changzhi and Yangquan would experience more significant increase (about 2000 RMB), equivalent to 5%-7% of their annual disposable income in 2015. This is because coal is relatively cheaper due to the abundant local reserve in these cities in Shanxi Province, hence expense rise would make a larger difference if the coal heating tradition was to be entirely abandoned. As a contrast, the additional cost increases would be lower (500–800 RMB) for rural households in Beijing and Tianjin, which are comparatively richer, and would only accounts for about 1% of their household income. This difference is also tied to the regional disparity of energy price subsidy for residential users, given that the government of relatively more developed city is usually more financially capable of providing fund support.

3.3.4. Impacts on social cost and benefit

Instead of examining emission reductions and energy expense increase separately as have been done in previous discussions, this section tries to more comprehensively investigate the overall policy impacts on social costs and benefits. Estimations were made under S1 for different cities to understand the equivalent economic losses and gains if scattered coal used by the building sector in "2 + 26 cities" would be entirely superseded (Fig. 8). Results show that for almost all cities covered, benefits of this policy reaped from reduced harm for climate and health are expected to outweigh the costs involved in project implementation, resulting a net social benefit of about 50 billion RMB for the 28 cities. This implies that the promotion of scattered coal substitution program is reasonable and efficient from the perspective of city's sustainable development. Health benefits, especially those generated from reduced productivity losses and medical expenditure related to chronic illness, would be much greater than climate mitigation benefits. This is caused by the offset of CO_2 emissions from newly

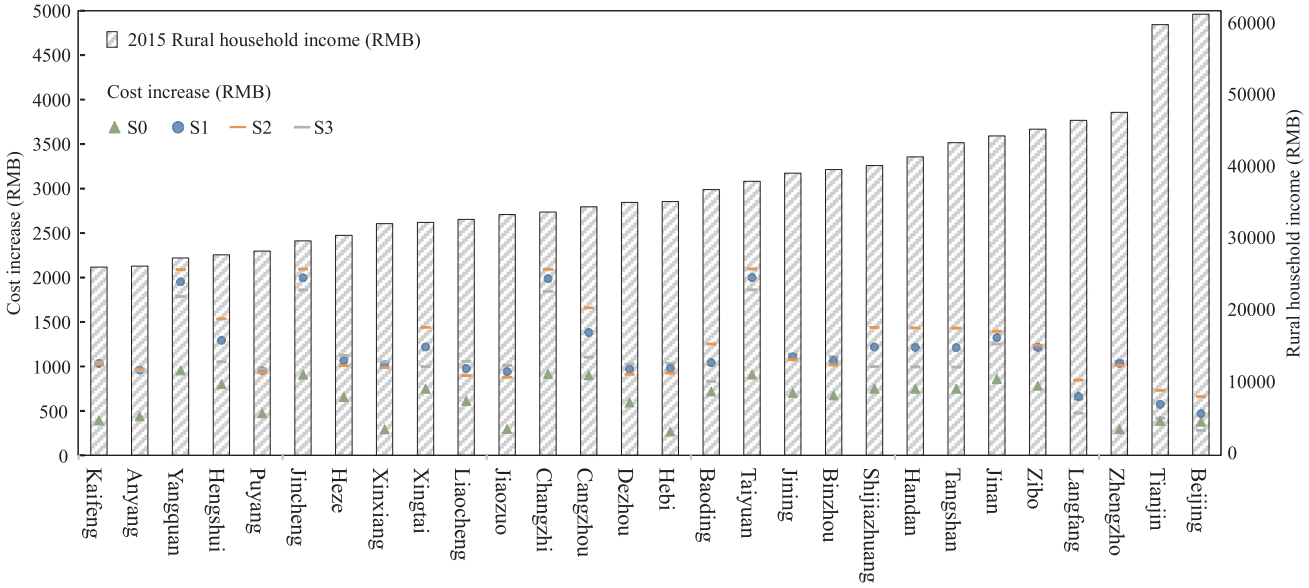

Fig. 7. Energy expense increase (under different scenarios) caused by the coal substitution policy for average rural household in "2 + 26 cities". Annual disposable household income for each city is also shown (the bars) and is arranged from low to high by city.

increased NG and electricity consumption. While for the social costs, capital investment for new clean heating equipment purchase and installation would play a much larger role compared with the operation costs, which mainly comes from increased energy expense and might bring non-negligible economic burdens for rural households.

Analysis by city suggests that the absolute value of both social benefits and costs are mainly determined by the amount of scattered coal used, which is closely related to status of economic development and size of population. Therefore besides the two megacities (Beijing and Tianjin), the social and economic influence of coal substitution policy would be comparatively stronger in several cities of Hebei Province (e.g. Baoding and Handan) because of their larger rural population and lower per capita income level. Moreover, two indicators, namely the share of the monetized benefit relative to Gross Regional Product (GRP) and the share of costs relative to local financial expenditure, were used to examine the policy impacts on local economy (Fig. 8). Results show that the overall social benefits account for about 3.1% of GRP in "2 + 26 cities", and this effect would be more pronounced for the less developed cities. This is explained not only by their smaller economy, but also by the higher fraction of population that

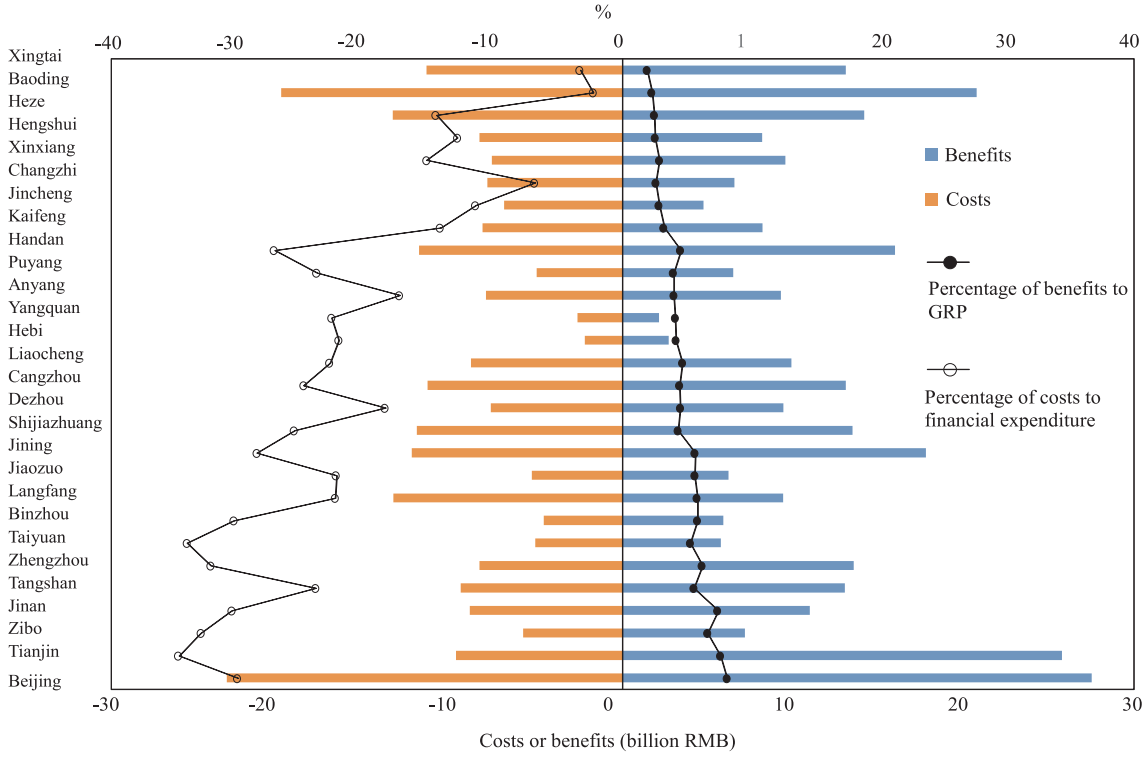

Fig. 8. Monetized social costs and benefits caused by scattered coal substitution policy by city, which are respectively presented as positive and negative values. Cities are arranged by per capita GDP in descending order. The marker lines are the percentage of benefits to Gross Regional Product (GRP) and the percentage of costs to local financial expenditure, respectively.

would free from exposure to the coal-induced pollution. When it comes to social costs, it is found that cities with higher substitution rate for electric heating tend to spend more given its greater initial investment compared to NG based stoves. However, even for cities with similar preference for the alternative fuel within the same province, the magnitude of costs relative to local finances would vary with the development status of cities. As the majority of the capital and operation costs would be covered by local government, the impacts of the policy costs are also expected to be larger and cause more economic burden for less affluent cities. For example, if scattered coal is to be completely eliminated, the costs of policy implementation in Heze (Shandong province) would almost equal to 30% the financial expenditure, much higher than that of the capital city (Jinan, 13%). The same goes for the comparison among cities of Henan Province. So lower per capita costs resulted from less intensive use of coal in more developed cities might explain their relatively higher net social welfare. Therefore the difficulties related to building energy transformation facing the less well-off areas would be more challenging. This is because it might on one hand subject low-income households to lower energy service quality due to insufficient penetrations of modern clean energy, while on the other hand subject local government to more fiscal pressures due to greater demand for government subsidies.

4. Conclusions and implications

4.1. Conclusions

Driven by the continuous improvement of living standard, China's building sector is expected to become a leading force in national energy-saving and emission reductions. Therefore it is of great necessity to characterize the spatiotemporal variations of building energy use to facilitate energy plan and policy implementation on city or finer scale. To better prepare the cities for the large scale transformation of building energy consumption in Northern China under scattered coal substitution policy, this study developed a GIS-based downscaling framework for China's building sector, and applied it to quantitatively evaluate the policy impacts on energy sustainability, pollution control, and carbon mitigation for the building sector of the "2 + 26 cities" during the 13th Five-Year-Plan (FYP). Some policy relevant conclusions can be drawn.

First, scattered coal reductions during 2015–2020 due to the implementation of coal-to-gas and coal-to-electricity policies in "2 + 26 cities" are expected to contribute about 33% to national total scattered coal reductions from the building sector. And the decline would be more evident in urban areas where stricter emission standards are imposed. Estimations show that about 78.8% natural gas (NG) increase and 19.4% electricity increase during the 13th FYP would be attributed to the coal substitution policy, which could help phase out coal use for space heating in rural areas, thus narrowing the gap of per capita clean energy consumption between urban and rural residents. The findings suggest that by examining the spatiotemporal distribution changes of energy consumption driven by both policy and socioeconomic factors, predictions of energy demand increase by city and sector could be made more accurately. This could be readily used to provide scientific information basis for provincial energy planning ranging from gas pipeline design and construction to electricity network expansion and upgrading in rural areas.

Second, considerable air pollutants reductions would be achieved through the clean energy substitution policy. Direct SO_2 and NO_x emissions from building energy use would be reduced by 78.2% and 44.5% in 2020, much larger than the average value set by national overall emission control target (15%) for the 13th FYP. And electricity substitution would be more competitive than NG substitution in cutting NO_x emissions, which can be largely explained by the fact that emissions of NO_x, a critical precursor of secondary aerosol, from natural gas combustion can be hardly avoided and ignored, especially for individual users without pollution control devices. With more and more cities set their own targets concerning the decline of ambient $PM_{2.5}$ concentrations, future air quality simulations aiming at emission reduction policies are of vital importance. Hence the high resolution emission inventory of the building sector constructed in this study might serve as basic input data for these atmospheric transport models.

Third, if no coal was allowed to be used in residential and commercial buildings in 2020, then for the building sector of "2 + 26 cities", per capita NG demand would increase by 24.2% from that under planned scenario (S0). This might induce potential risk that the construction of NG pipelines would fall behind the rapid gas demand growth. Moreover, severe inadequacy of NG strategic storage capacity in the six provinces/municipalities, which amounts to only one fifth of that in European countries of similar size, might constitute another obstacle for the large scale implementation of coal-to-gas policy. As a contrast, electric heating, such as air source heat pump, is usually more efficient and can take advantage of the favorable policy for lower valley price. It is even considered as a promising solution to the oversupply problem of renewable electricity. Besides, the energy expense increase due to shifting to clean energy would be greater for rural families in less affluent cities (5–7% of their annual disposable income), and this increase is expected to be smaller under S3 compared with that under S1 and S2 for most cities.

Generally, energy savings under coal-forbidden scenarios (S1, S2 and S3) would be greater than that under planned scenario (S0), so do emission reductions of SO_2 and $PM_{2.5}$. Wider application of electricity substitution in the building sector (S3) could help accelerate the overall reductions of NO_x emissions, considering that decarbonization and ultra-low emission standards for local air pollutants would be more strictly and rapidly implemented in power plants. The results of this study concerning city-level building energy demand changes during the 13th FYP might be used to adjust policy decisions and retrofit goals of the respective cities, which should be made on the basis of local gas supply source and strategic storage.

Finally, the actions aiming at eliminating scattered coal from the building sector are expected to generate net social benefit when taking the avoided health and climate damage into account. Generally cleaning up scattered coal would bring health and climate benefits equivalent to 3% of GRP in the 28 major northern cities, and the accompanying capital and operation costs would amount to 17.5% of the local financial expenditure. For the less developed cities which often rely more on scattered coal for heating, although greater reduction of coal-related indoor pollution might deliver larger social benefits compared with other cities within the same province, the costs would constitute heavy economic burdens. This might lower public acceptance for the potential welfare since it is often difficult for the low-income population to recognize the value of improving health and environment in a short time. While for the more developed cities, they might face smaller task of clean heating retrofit and are often equipped with greater economic strength to provide subsidies. This might be one of the reasons why electricity based air-source heat pump and thermal energy storage heater tend to be more popular in these areas despite of their relatively higher initial costs for installation.

4.2. Implications

Although great efforts have been devoted to establishing historical carbon emission dataset on city scale, attempts have seldom been made for future predictions of air pollutant emissions, especially regarding multiple cities given the bulk of detailed information required by the bottom-up approach. Therefore, it is of great necessity to develop a spatial downscaling framework to facilitate city-level energy management and emission control, especially for the building sector, which has become an important actor in low-carbon development of cities but has little open data available for quantification. This framework should be able to account for the spatial variations of socioeconomic and policy

drivers of future building energy consumption, so that national/provincial plans and targets related to energy and emissions could be disaggregated into city or finer scale.

Besides, the choice of substitution fuels for the traditional coal should be made by systematic comparisons from various perspectives, such as energy accessibility, affordability and potential environmental benefits. Given that limit NG supply from both domestic and international market, as well as required NG pipeline and storage capacity, large scale application of natural gas (NG) as primary space heating source might not be suitable for most Chinese rural areas. On the other hand, electrification rate in rural areas of northern cities is expected to increase much faster than the coverage of NG pipeline network. It is believed that the increasing electrification rate in building sector would play a more and more important role for low carbon development considering the increasing share of new and renewable energy used for power generation.

As indicated by city-scale cost and benefit analysis, the overall positive policy impacts brought by health/climate benefits would prevail over the project costs. However, it would still be difficult for the local administration of the less developed cities, in which more people might be exposed to scattered coal use and indoor pollutions, to address the pressures resulting from both financial subsidies and strict execution. The main challenge of promoting “coal-to-gas/electricity” is the relatively high initial investment which calls for long term government subsidies. Therefore the fundamental of the sustained shift to clean heating behaviors might lie in reducing technical costs while improving income level. It is suggested that policy should be made based on the economic development conditions of different cities. For the more developed cities, wider and earlier application of electricity based heating would be feasible and would help more efficiently allocate limited social resources considering their larger per capita net social gains. While for the less developed cities, it is crucial to ensure official subsidies on the basis of enhancing local economic strength, which should rely more on low-carbon industry transformation.

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Conflict of interest

The authors declare that they have no conflict of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2018.12.051.

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